Efficient dual-wavelength laser at 946 and 1064 nm with compactly combined Nd:YAG and $Nd:YVO_4$ crystals

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LETTER

Efficient dual-wavelength laser at 946 and 1064 nm with compactly combined Nd:YAG and Nd:YVO_4 crystals

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Abstract
We originally employ a compact combination of a Nd:YAG crystal and a Nd:YVO_4 crystal to develop an efficient dual-wavelength laser operating at 946 and 1064 nm. We exploit a short Nd:YAG crystal to generate 946 nm laser by reducing the reabsorption loss and a follow-up Nd:YVO_4 crystal to generate a 1064 nm laser by absorbing the residual pump light. The output power ratio between the 946 and 1064 nm emissions can be flexibly adjusted from 0.3 to 0.9 by varying the separation between the two output couplers. At an incident pump power of 17 W, the total output power is generally higher than 5.2 W, with an overall optical-to-optical efficiency greater than 30%.

(Some figures may appear in colour only in the online journal)

Simultaneous dual-wavelength lasers are of great interest in a variety of areas, such as laser spectroscopy, nonlinear optics, and medical applications [1–3]. By using diode pumping, simultaneous dual-wavelength lasers with operation on two four-level transitions, 1.06 μm $^4F_{3/2} \rightarrow {}^4I_{11/2}$ and 1.3 μm $^4F_{3/2} \rightarrow {}^4I_{13/2}$, have been realized with single Nd:YVO_4 [4, 5], Nd:$GdVO_4$ [6], or Nd:YAG [7] crystals. Also, simultaneous dual-wavelength lasers with operation on a quasi-three-level transition and a four-level transition have also been reported in various single Nd-doped crystals [8–10]. However, dual-wavelength operation on $^4F_{3/2} \rightarrow {}^4I_{9/2}$ and $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions has to confront two difficulties. One is the significant reabsorption loss of the quasi-three-level transition; the other is the large difference between the emission cross sections of the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ and $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions. A short laser crystal is usually employed to reduce the reabsorption loss in the quasi-three-level emission. Nevertheless, a considerable amount of pump light was not absorbed by the gain medium. As a consequence, optical-to-optical conversion efficiencies were always below 20% for dual-wavelength lasers on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ and $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions.

In this letter we exploit overlapping collinear resonators to develop an efficient dual-wavelength laser with emission at 946 and 1064 nm with an optical-to-optical conversion efficiency up to 30%. As usual, a short Nd:YAG crystal is employed as the gain medium to generate 946 nm emission. The novelty is that we compactly join a Nd:YVO_4 crystal to the Nd:YAG crystal to absorb the residual pump light and efficiently generate 1064 nm emission. More importantly, the output power ratio between the 946 and 1064 nm emissions P_{946}/P_{1064} can be flexibly adjusted by simply varying the separation between the two output couplers for the 946 and 1064 nm resonators. At a pump power of 17 W, the total output power is generally greater than 5.2 W with a power ratio P_{946}/P_{1064} in the range 0.3–0.9. It is, to the best of our knowledge, the highest efficiency ever achieved in dual-wavelength lasers operating at 946 and 1064 nm.

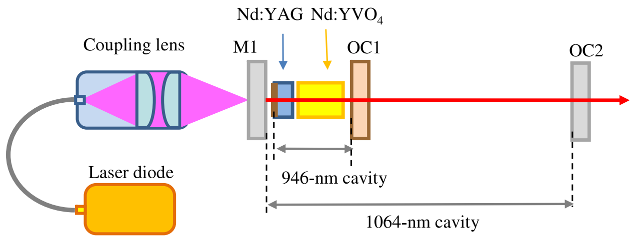

Figure 1. Cavity configuration for the dual-wavelength operation.

Figure 1 shows the cavity configuration for the dual-wavelength operation. The cavity for the 946 nm transition was formed by a coated gain medium and a flat output coupler (OC1). The active medium for 946 nm emission was a 1.1 at.% Nd:YAG crystal with a length of 2 mm and a transverse aperture of 3×3 mm^2. The front surface of the Nd:YAG crystal was coated to be highly reflecting at 946 nm ($R > 99.8\%$) and highly transmitting at 808 and 1064 nm ($T > 95\%$). The rear surface of the crystal was coated to be anti-reflective at 946 and 1064 nm ($R < 0.2\%$). The front surface of OC1 was coated to be partially reflecting at 946 nm ($R = 95\%$) and highly transmitting at 1064 nm ($T > 99\%$). The rear surface of OC1 was coated to be anti-reflective at 946 and 1064 nm ($R < 0.2\%$). The resonator for the 1064 nm transition was composed of an input flat mirror (M1), a gain medium, and a flat output coupler (OC2). The flat mirror M1 was coated to be anti-reflective at 808 nm ($R < 0.2\%$) on the entrance face, and highly reflecting at 1064 nm ($R > 99.8\%$) and highly transmitting at 808 nm ($T > 95\%$) on the other surface. The gain medium was an *a*-cut 0.2 at.% Nd:YVO_4 crystal with a length of 6 mm and a transverse aperture of 3×3 mm^2. Both end surfaces of the Nd:YVO_4 crystal were coated to be anti-reflective at both 946 and 1064 nm ($R < 0.2\%$). Note that the Nd:YVO_4 crystal was compactly joined to the Nd:YAG rod to absorb the residual pump light. More importantly, the Nd:YVO_4 crystal did not cause significant losses to the 946 nm emission. The front surface of OC2 was coated to be partially reflecting at 1064 nm ($R = 10\%$) and highly transmitting at 946 nm ($T > 90\%$). The rear surface of OC2 was coated to be anti-reflective at 946 and 1064 nm ($R < 0.2\%$). The separation d between OC1 and OC2 could be adjusted in the range of 1.5–4.0 cm to obtain different output power ratios P_{946}/P_{1064}.

The pump source was a 20 W 808 nm fiber-coupled laser diode with a 200 μm fiber core diameter and a numerical aperture of 0.16, reimaged into the laser crystal through a pair of focusing lenses with focal lengths of 50 mm and 85% coupling efficiency. The pump spot radius was approximately 300 μm. The spectral information was monitored by an optical spectrum analyzer (Advantest Q8381A) employing a diffraction grating monochromator with a resolution of 0.1 nm. The total length of the dual-wavelength resonator is approximately equal to the separation d plus 1.0 cm.

The absorption percentage of the Nd:YAG crystal for 808 nm pump light was found to be approximately 53%. In other words, the residual pump light entering the Nd:YVO_4 crystal was approximately 47%. The dual-wavelength system

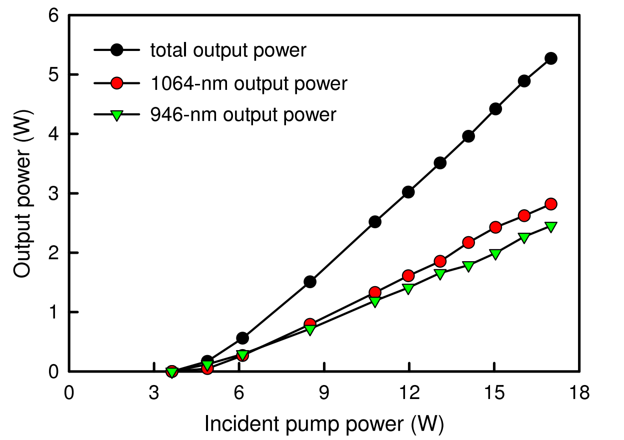

Figure 2. Output power versus incident pump power for simultaneous dual-wavelength emission at 946 and 1064 nm with a separation of $d = 5.0$ cm.

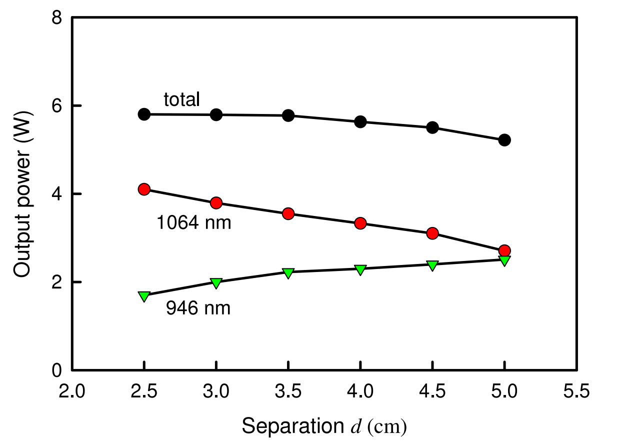

Figure 3. Output powers at the 946 and 1064 nm emissions as a function of the separation d at the maximum pump power of 17 W.

was initially optimized at 946 nm without the output coupler OC2 shown in figure 1. By introducing OC2 into the laser cavity, simultaneous lasing was achieved at 946 and 1064 nm. Figure 2 shows the output power versus the incident pump power for simultaneous dual-wavelength emission at 946 and 1064 nm with $d = 5.0$ cm. It can be seen that the output powers of both wavelengths monotonically increased as the pump power increased. We also found that the fluctuations in the output powers of each wavelength were less than $\pm 3\%$. The reduction of the competitive interaction between two wavelengths is partly due to the separation of the output couplers for each wavelength. The lasing threshold was approximately 3.6 W for both wavelengths. At the maximum pump power of 17 W, the total output power was up to 5.2 W, where the individual output powers for the 946 nm and 1064 nm emissions were 2.48 W and 2.72 W, respectively.

Shrinking the cavity length can increase the average photon density, so the ability to compete of the relevant transition can be enhanced. Therefore, the output power ratio P_{946}/P_{1064} can be flexibly adjusted by varying the separation d between OC1 and OC2. Figure 3 shows the output powers of the 946 and 1064 nm emissions as a function of the

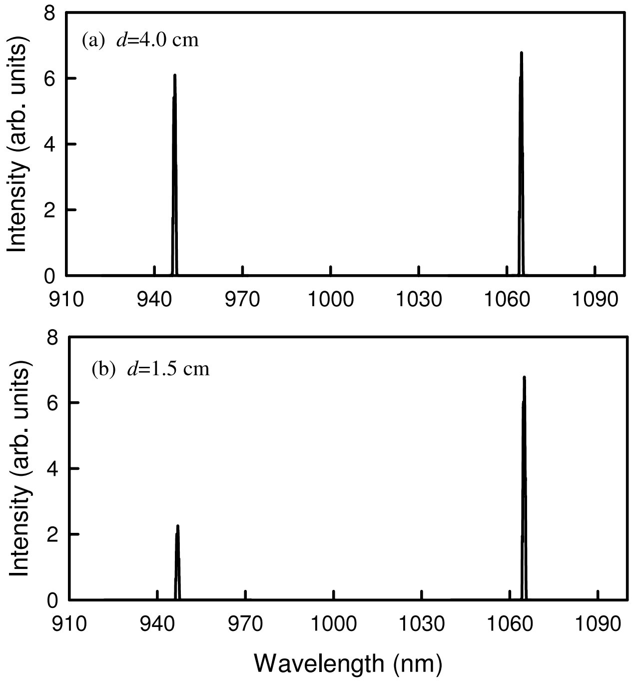

Figure 4. Optical spectra obtained with two different separations of $d = 1.5$ and 4.0 cm at the maximum pump power of 17 W.

separation d at a maximum pump power of 17 W. It can be seen that when the separation d varies from 2.5 to 5.0 cm, the output power ratio P_{946}/P_{1064} can be changed from 0.3 to 0.9. Figure 4 shows the optical spectra obtained with two different separations of $d = 2.5$ and 5.0 cm at the maximum pump power of 17 W. The overall optical-to-optical efficiency was found to be greater than 30%. To the best of our knowledge, this is the highest efficiency reported to date for a dual-wavelength laser at 946 and 1064 nm. The beam quality factors were found to be approximately 1.3–1.5 for both emissions.

In summary, we have developed an efficient dual-wavelength laser operating at 946 and 1064 nm with a compact combination of a Nd:YAG crystal and a Nd:YVO_4 crystal. A short Nd:YAG crystal is used to reduce the reabsorption loss when generating 946 nm laser light and a follow-up Nd:YVO_4 crystal is employed to absorb the residual pump light for generating 1064 nm laser light. When the separation between the two output couplers was 4.0 cm, the individual output powers at 946 and 1064 nm at an incident pump power of 17 W were found to be up to 2.48 W and 2.72 W, respectively. The output power ratio between the 946 and 1064 nm emissions P_{946}/P_{1064} can be adjusted from 0.3 to 0.9 by varying the separation between the two output couplers from 1.5 to 4.0 cm. The overall optical-to-optical efficiency for the total output power was generally higher than 30%.

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